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P R E F A C E

This study is the most recent of several which have been conducted at the St. Anthony Falls Hydraulic Laboratory in the interest of better clarifying the role of micro gas bubbles in the inception of cavitation on propellers and other hydrodynamic bodies. Most of these studies have dealt with the problem of determining the presence and influence which such bubbles have in modelled cavitation tests in water tunnels. In contrast the current study constitutes a preliminary attempt to measure the presence of such bubbles as a result of ship motions in natural waters. The study relates to bubble measurements in undisturbed waters, in dynamically disturbed waters, and in the decaying wake following disturbance. The eventual clarification of model-prototype cavitation correlations and of the generation and decay of acoustic wakes is dependent on further laboratory and field studies of this character.

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I. INTRODUCTION

Studies of the basic mechanism of the inception of cavitation have been conducted at the St. Anthony Falls Hydraulic Laboratory for a number of years. These studies and others have served to establish that the laboratory investigation of cavitation inception on propellers or other hydraulic machines is critically dependent on the gaseous micro-bubble structure of the test water [1]*. The studies have further indicated that this micro-bubble structure is dependent on a variety of solid and chemical contaminants but is probably most sensitive to the dissolved gas content and the prior history of static and dynamic pressurization conditions. While positive static pressure cycling can exert an important influence on this gasification, in the practical case, it is the negative dynamic pressure exposure which appears most significant to bubble formation.

In the case of recirculating flow facilities for modelled cavitation studies the significant negative pressure centers are those which combine the low core pressure of a local shear vortex with a low ambient pressure. The tunnel regions most productive of these pressure centers are the boundaries of the cavitation test section and the low pressure areas of the pump blading. It must be recognized, however, in these modelled tests that the sustained dynamic disturbance and low ambient pressures inherent to the water tunnel flow will produce and maintain larger and more numerous gas nuclei than should normally exist in prototype waters. For the prototype case where the static pressure is normally at or above atmospheric and where the basic dynamic disturbance is slight, the bubbles should be much smaller. Since the size of the bubble nuclei is believed critical to the inception of cavitation in either natural or test waters it is important to the eventual similitude of propeller tests that a clearer understanding of this nuclei structure be obtained for the test waters.

If the literature is examined for data on the free gas content existing in natural waters or more important the gasification existing just

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*Numbers in brackets refer to the List of References at the end of this paper.

upstream of a propeller, virtually no data are to be found for either locale. The reason for this is understandable, however, if we examine the investigations of Strasberg [2] and Iyengar and Richardson [3]. These studies establish that natural forces should and do promote the solution of free gas in quiet waters until only a few stable bubbles of very small dimension exist. It was Strasberg's conclusion that "water which has been standing undisturbed for several hours contains fewer than one bubble per cubic centimeter with radii in the range 3×10^{-4} to 9×10^{-4} cm, and that the total volume of undissolved air in this size range is less than 6×10^{-10} cubic centimeters per cubic centimeter of water".

Since these very small values are difficult to measure in the laboratory it is unrealistic to expect to measure like values under field conditions. On the other hand even natural waters which have been sufficiently disturbed should show evidence of additional gasification. It is the objective of this study to show that gasification significant to the inception of cavitation is produced by normal boundary action on ships and that such gasification is subject to measurement.

Considerable early research has been summarized in Ref. [4]. In this work measurements with standard fathometer and sonar acoustic gear established that bubble elements were detectable in concentrations as small as one part in 10^7 by volume. The work further showed that this gas took from 30 to 45 minutes to decay to a size beyond ready acoustic detection.

While establishment of these values for propeller wakes was important in the field of acoustic detection it failed to evaluate the gasification which is important to the propeller designer, namely the conditions which exist in the water entering the propeller. The current investigation, on the other hand, is an exploratory study in this direction.

Studies of gasification in a water tunnel [5] have already demonstrated that acoustic techniques can be employed for such measurements and separate investigations are now underway at the St. Anthony Falls Hydraulic Laboratory to develop such instrumentation for use in the cavitation tunnels at the David Taylor Model Basin.

This report deals with the application of similar techniques to the measurement of gasification in limited field tests. These applications being exploratory in nature used available instrumentation and fresh water

environments as a first approximation to aid in establishing the more extensive tests which will be needed for an ultimate clarification of prototype gas conditions at sea.

The tests described herein deal first with preliminary studies of gasification due to a small boundary layer condition generated on a rotating disk in a laboratory tank. These studies were followed by field measurements of gasification due to a large boundary layer which subsequently flowed through a large propeller type hydroelectric turbine. The last tests dealt with gasification measurements in the wake of a Lake Superior ore freighter and in the wake of a Mississippi River towboat.

The latter tests were primarily concerned with the decay time of the gas bubbles in returning to the normal ambient condition.

II. MEASURING TECHNIQUES

The gasification in these studies was measured by an acoustic attenuation system. This included a noise source and a pick-up hydrophone submerged in the test water. Since each bubble in the water elastically resonates in response to a certain frequency of pressure pulsing, pulsation energy will be selectively absorbed or attenuated by natural damping factors. The discrete frequencies which are attenuated in a broad band noise transmission through the test water will therefore identify the size of the bubbles present and the relative amount of attenuation will be an index of the number or concentration of such bubbles.

Unfortunately the measurement of gasification by this method encounters difficulties which limit the use in practice. Principal among the difficulties are the reflections from surrounding boundaries which serve to obscure the transmission and inherent noise and damping which reduce the sensitivity to the lower gas concentrations. Various pressure transducers and housing configurations were tested in the early part of the program but none proved more practical than simple submersion of two standard Navy transducers in an open water surrounding.

The open surrounding was employed in all studies where the relative water velocity was essentially zero. In those studies where measurements were made in moving water the transmission path was housed in a small rectangular plexiglas chamber. This chamber presented a more troublesome

reflection system than the open setting but had the advantage of stabilizing the reflection pattern and of protecting the sensitive transducers from damage. The reflection pattern within the chamber could be identified and to a considerable extent could be nullified by providing the pick-up hydrophone with a mechanical traversing system which would permit variation of the transmission path length during observations.

The noise source in these tests was a Bell 5A transducer with a diaphragm of 2-1/2-in. diameter. The source was driven by a General Radio Random Noise Generator Type 1390B.

The pick-up hydrophone was a Chesapeake TP 210. The active head of this unit was approximately 3/4 in. in diameter and 2 in. long.

As will be pointed out later it would have been desirable to extend the frequency coverage to much higher values but the tests in general were confined to the range of 20 to 200 kc because of the inherent limits of the hydrophone and readout system. These limits were, however, considered entirely adequate to measure the larger sizes of bubbles (up to 10^{-2}-in. diameter) which are believed to be normally involved and most significant to prototype propeller cavitation. In the working instrument the hydrophone axis was placed parallel to the noisemaker diaphragm with the transmission distance made variable by traversing from about 3/4 in. to 4 inches.

The hydrophone signal was amplified and fed to a Panoramic Ultrasonic Analyzer Model SB-7bz for visual study on the analyzer cathode ray tube or for graphic plotting on a connected x-y recorder. In field studies the original signal was tape recorded on a Precision Instrument Company Model π and later fed to the analyzer for graphic plotting.

In preliminary tests the recordings were analyzed in detail for the attenuation of specific frequencies in order to obtain specific bubble size concentrations in accord with Ref. [6]. However, the volume of data resulting from this type of analysis proved excessive for the more general perspective type of gasification measurements which were deemed meaningful to this study. As a result the data are presented herein as a simple wide band attenuation plotting which rather directly shows the bubble sizes present but which shows the concentrations in only a very relative way. Although concentrations were not evaluated for the test data, laboratory checks on the equipment established that the sensitivity over most of the 20 to 200 kc range

coverage was of the order of one part in 10^7 by volume. The threshold acoustic readout pattern of the field test setup was frequently checked in aged and undisturbed laboratory water.

Earlier studies in the laboratory had established that measurements in near-saturated gasified waters frequently were troubled with false attenuation signals due to adherent bubbles on the active surfaces of the transducers. Laborious manual brushing procedures were first employed to remove these troublesome bubbles but later tests indicated that the bubbles could be effectively removed by simply raising the transducers out of the water and then resubmerging. In field tests where such direct removal was impractical the plexiglas housing was used as a bell jar and compressed air was briefly injected and vented to provide an air flushing drainage cycle. This bubble removal procedure was performed just prior to each attenuation measurement. (More recent tests in the laboratory have given some indication that such simple flushing may not have sufficiently removed all of the smaller bubbles.)

The plexiglas housing chamber was also attached to a topside water pump which in earlier tests provided a continuous low-disturbance change of test water in the chamber. The water sample was drawn through ports near the bottom of the chamber. In the case of moving water the samples were drawn from ports positioned in stagnation zones of the housing exterior. In later tests the air flushing procedure for adherent bubble removal was also found adequate for bringing a fresh sample of water into the testing chamber.

III. MEASUREMENT OF LABORATORY WATER DISTURBED BY A ROTATING DISK

Earlier studies [5] had indicated the approximate size range and concentration of bubbles which might be expected in a water tunnel environment, and other studies [4, 7] give some indication of the gasification present in propeller wakes. There is, however, no indication of measurements of the bubble structure which might be expected when the disturbing dynamics are relatively weak in character, as they are in a ship's boundary layer. In consequence one of the first studies under this program was the measurement of gasification in laboratory waters with a dynamic system in which the disturbance conditions could be progressively increased from a low initial level.

The test setup consisted of the previously described acoustic system monitoring the fresh water in a small metal tank (18 in. by 24 in. with

water depth of 16 in.) in which dynamic disturbance was provided by a rotating smooth disk. The aluminum disk of 3-7/8-in. diameter and 1/2-in. thickness was rotated by a variable speed submersible electric motor. The motor was mounted with the disk down and horizontal. The plane of the disk was about 4 in. below the water surface. The transducers were spaced to transmit through about 2 in. of water.

The graphical output of the x-y plotter was manually replotted as shown in Fig. 1. This figure gives the measured acoustic attenuation as a function of the frequency components of the imposed random noise. The abscissa is also given in terms of the resonant gas bubble diameter based on the equation $d = 2/\omega \sqrt{3KP/\rho}$ where ω is 2π times the resonant frequency, K is the adiabatic gas exponent for air, and P is the gas pressure in the bubbles (for large bubbles nearly equal to the ambient pressure).

Since the purpose of this study was to provide a measure of influence of dynamic disturbance on gasification, disturbance was varied by varying both the disk speed and roughness. For the first run, the acoustic transmission was measured in the tank for the water in a long undisturbed condition. These measurements constitute the horizontal base line of the plottings. Following this the motor was progressively speeded up in two steps and acoustic measurements were made as shown. The water temperature was 65 F.

Following the smooth-disk acoustic measurements, the motor was stopped and, at approximately 5-min intervals new acoustic measurements were made. The latter measurements (unplotted) showed a progressive reduction of free gas and a return to essentially the characteristics of the originally undisturbed water. This decay or return required about 25 min.

After the normalizing had been accomplished, the disk was roughened by the addition of two small machine screws or pegs. These screws were about 1/8 in. in diameter and projected about 1/2 inch. They were placed perpendicular to the disk face near the disk edge and at opposite ends of a disk diameter. Rotation of the disk with these attached pegs produced the shear vorticity of the disk face plus the strong separation vorticity of the cylindrical pegs. The attenuation resulting with this combination is shown in the upper curve of Fig. 1.

Preliminary tests in this series were run in a large tank with the transducers placed to measure the characteristics of the flow sheet being

centrifugally discharged from the disk edge. These tests failed to detect any measurable gasification until the size of the tank was reduced and the length of the run extended so as to provide a given water unit with an adequate disturbance exposure. It appears that the rate of input of disturbance energy has a threshold which must be exceeded if gas evolution is to exceed gas resolution. It is noteworthy that the bubble measurements of Ref. [7] found that the size of wake bubbles increased with the length of ship thus also indicating that the length of exposure to boundary layer vorticity is a factor in the development of bubbles.

The following significant features may be noted from these simple tests:

(a) With sustained exposure a relatively weak turbulent boundary layer is capable of generating sufficient vorticity to grow gas bubbles under normal atmospheric conditions in normally saturated water. The extent of the exposure appears to be a factor in the production of bubbles.

(b) The acoustic nature of the gas measuring instrumentation served to establish that characteristic cavitation noise did not occur during the bubble generation. It may thus be concluded that shearing vorticity alone grew the bubbles.

(c) The gasification increased with speed but measurable values were obtained at peripheral velocities as low as 20 ft per sec in these tests and even at 10 ft per sec in tests which are not shown.

(d) The gasification occurred in a large range of bubble sizes but the larger sizes of bubbles which were grown (≈0.010-in. diameter) were considered suitable nuclei for cavitation because they had a critical expansion pressure which was only slightly less than vapor pressure.

IV. MEASUREMENT OF MISSISSIPPI RIVER WATER DISTURBED BY CHANNEL FRICTION AND BY A PROPELLER TURBINE

The earlier tests with a smooth rotating disk in a tank of water had indicated, as shown in Fig. 1, that sustained exposure of water to even

a relatively weak turbulent boundary layer would generate sufficient vorticity to cause growth of micro-bubbles in a normal water. These tests indicated that the gasification increased with speed but that measurable gasification could be detected with speeds as low as 10 fps. Since the relative water velocity over a ship's hull is usually greater than 10 fps it is logical to assume that propellers mounted downstream of a lengthy hull boundary layer will be supplied with water having a significant gasification. While measurement of gasification conditions ahead of an actual propeller must ultimately be pursued to clarify this influence of the hull on propeller cavitation inception neither suitable instrumentation nor ship facilities were available for such tests at St. Anthony Falls. It was reasoned, however, that similar gasification might be studied in the boundary layer of a long open-channel flow and that simple instrumentation could be adapted. The most suitable channel for the conduct of such studies at St. Anthony Falls was a long, rough-walled headrace canal leading to a hydroelectric power plant containing a propeller type turbine oriented as shown in Fig. 2. This arrangement had the advantage of permitting examination of gasification involving both stationary and moving boundaries.

This flow system which is located at St. Anthony Falls on the Mississippi River consists of a headrace canal which draws water from a large headwater pool and conveys it to a short pressurized steel penstock. The penstock in turn conveys the water to a variable pitch propeller turbine which discharges through a diffusing draft tube to the tailwater pool at the Falls.

Measurement of water gasification was made at points A, B, and C as shown in Fig. 2. Point A was assumed to yield an ambient or essentially undisturbed condition of the water because of the very low velocity conditions which prevailed at and upstream of this point. Point B was selected because it permitted measurement of gasification of the general flow following exposure to considerable boundary layer disturbance along the rough masonry walls of the canal. This disturbance was assumed to have some parallel to the length and roughness conditions for flow over a ship's hull. Point C was selected as a measure of the gasification following disturbance by the blading of a powerful propeller system.

Disturbance conditions prior to Point B were considered to be primarily due to the vorticity generated by flow over the 300-ft length of rough masonry floor and side wall surfaces of the canal (roughness projections up

to 3 in. high in a canal of width 54 ft and depth 17 ft). However, disturbance was also introduced from flow separation vorticity shed by the two non-streamlined bridge piers near the upstream end of the canal. The mean velocity through the canal during the test measurements was about 4 fps. The energy loss between Points A, a flow distance of about 300 ft, and B was estimated at about one quarter foot pound per pound of water.

Disturbance conditions between Points B and C were caused by flow through the trash screen just downstream of Point B, the 13-ft diameter penstock (mean velocity of 5 fps), the distribution chamber, the flow controlling wicket gates, the turbine blading, and the flow diffusing elbow draft tube. While the turbine was a modern (1954) design which had been installed in the rehabilitation of an older powerhouse, dimensional limitations prevented the use of a best efficiency flow distribution scroll. In consequence the turbines could be operated only up to 62 per cent of full gate with some disturbance occurring just upstream of the blades and with some cavitation on the blades. In addition the surrounding conditions differ from those of a marine propeller in that the general flow is exposed to subatmospheric pressures near the trailing edge of the blades and for a considerable distance into the draft tube before normalizing to atmospheric pressure at the draft tube exit at Point C. The measured relative vacuum at the draft tube entrance during the tests was 7 in. of mercury. The mean entrance velocity of the draft tube was about 24 fps and the mean exit velocity was about 7 fps.

The turbine had a nominal rating of 3500 hp under a 48-ft head, a blade diameter of 6 ft and a shaft speed of 277 rpm.

For the conditions of test the output energy efficiency was estimated at approximately 80 per cent of the plant head of 48 ft. On this basis the energy loss or disturbance energy amounted to about 4.5 to 5 foot pounds per pound of water and largely occurred in a flow length of less than 40 ft.

In the gasification tests at Points A, B, and C the measurements were made with the previously described acoustic transducers protectively housed in a rectangular plexiglas chamber of 3 in. width, 5 in. breadth, and 24 in. height. The test fluid was gently drawn through the test chamber during these tests. At Point A, where the dynamic head of the stream was very low, this circulation was assisted by an external suction pump. At Points B and C, where the dynamic pressure was appreciable, through-flow circulation

was maintained by venting the chamber at positive and negative dynamic pressure apertures. For all test locations the inflow or sampling aperture was consistently placed approximately 6.5 ft below the free water surface to minimize the possible entrance of surface entrained air. These tests were made with a river water temperature of 74 F and showed a Van Slyke total air content of about 27 ppm by weight. The saturated total gas value for water of 74 F is given as about 24 ppm exclusive of the dissolved carbon dioxide which was estimated at 2 ppm in this case. On this basis the water was probably slightly supersaturated.

The test measurements were made with the noisemaker and pick-up transducers transmitting through approximately 4 in. of test water. The resulting acoustic recording re-plots for test points A, B, and C are shown in Fig. 3. These original recordings were manually smoothed and replotted to give emphasis to the acoustic attenuation in the same manner as was previously employed for Fig. 1. In Fig. 3 the data for test location A constitute the horizontal base line or an assumed ambient condition of zero free gas.

Figure 3 is significant in that it shows (location B) a measurable gasification of moderate size range resulting from flow over a long rough boundary at a relatively low velocity. Subsequent exposure of this water to a more intense disturbance and concurrent with reduced ambient pressures resulted (location C) in a very substantial increase in the free gas over a wide range of bubble sizes. The larger bubbles (0.0025-in. diameter) generated by even the low velocity flow over the long stationary boundary have a critical cavitation pressure which is only about 1 ft of water head less than vapor pressure and hence could readily serve as nuclei for blade cavitation.

Attenuation below approximately 10 kc was not measured although large numbers of bubbles of diameters up to 0.2 in. were observed at the tailrace water surface in the vicinity of location C. It is not known whether these actually existed at the subsurface position of the sampling or whether they represent other coalescence or entrainment processes in this extremely turbulent region.

V. MEASUREMENT OF LAKE SUPERIOR WATER DISTURBED BY AN ORE FREIGHTER

The canal-turbine tests described in Section IV were intended to very roughly simulate the gasification for a ship type boundary layer and a

following propeller system. While these tests produced data giving useful insight into pertinent energy and gasification conditions within the system, the nature of the relative velocity in the confined river channels downstream of the propeller turbine could in no sense simulate the wake decay conditions of a marine propeller. For suitable studies of this nature both a powerful propeller system and an infinite discharge pool were required. The simplest answer to these requirements was the actual measurement of a ship's wake. The largest ship wakes conveniently available to study by the Laboratory were the wakes of ore freighters on Lake Superior.

The selected test site was the shipping lane for ore boats outgoing from Two Harbors, Minnesota on the north shore of Lake Superior. This area was about one mile offshore in waters in excess of 200 ft deep.

The test equipment consisted of the acoustic gear described in Section II with the plexiglas housing chamber arranged for air flushing. The assembly was suspended from a free riding float with the transducer elements submerged approximately 6 ft. The float was maintained abeam of a small commercial fishing boat which housed the recording gear and personnel.

The test was conducted on September 22,1962 with a strong offshore or NNW wind prevailing over the lake area and with high wave conditions on the main lake. However, in the lee of the shore where the test was conducted only a light wind prevailed with a random wave pattern having heights from 2 to 3 ft.

The lake water was very clear and had a temperature of 51 F. Van Slyke gas measurements indicated that the water was near saturation with air for the prevailing temperature. The latter observation was consistent with other observations [8] which indicate that the oxygen content of the lake is saturated or supersaturated at virtually all times. These studies [8] have also shown that the lake in late summer generally has a layer of warmer water 50 ft or more in thickness which overlies cold (40 F) bottom waters with a well-defined thermocline.

The target ship was the John Hulst of New York with test characteristics as follows: total loaded tonnage 14,000, length 590 ft, beam 60 ft, draft 30 ft, single prop, 2000 hp turbine, prop diameter 15 ft 6 in., prop pitch 14 ft 6 in., 80 rpm, speed 11 kts, prop center to keel 9 ft.

For the test run the wake of the passing target ship was first quickly marked by spar buoys and dye. The instrument was then successively positioned along this wake line at about 100-ft spacings. The first recording was made approximately 12 min after the passage of the target ship with a total of seven records being made at approximately 12-min intervals. These were followed by an ambient water test several hundred feet away from the wake area.

A white water wake was evident for only a few feet astern of the target ship and no visible bubbles were evident in the very clear water at any crossing of the wake. These visual evidences were markedly different from the long trailing white wakes usually observed behind ocean-going vessels [4].

Graphic attenuation-frequency plotting of this recorded test data served to confirm the visual observations in that none of the tests gave significant evidence of the presence of bubbles except in the frequencies above 160 kc. (Bubbles resonant to these frequencies are normally subvisual in size.) This absence of larger size bubbles was quite surprising and could only lead to the conclusion that either the bubbles were not generated in significant numbers for the test conditions or that they suffered decay at a more rapid rate than our earlier laboratory tests or the field tests of Ref. [4] would indicate.

Some insight into the bubble generating potentials of the target ship may be gained from an evaluation of the energy disturbance conditions. According to the findings of Ref. [4], the dimensions of a ship's wake are about 2.5 times the ship's beam and 1.5 times the ship's draft at a point where the width stabilizes a few ship's lengths astern. If these dimensions are applied to the John Hulst the wake cross section is about 6700 sq ft. At 11 kts speed the disturbed wake is being generated at about 7,700,000 lb per sec. If the wave energy of the ship and other losses are considered small and if it is generously assumed that the full 2000 hp output of the turbine is ultimately delivered to this wake, in this case the energy output is 1,100,000 foot pounds per sec. This is equivalent to 0.14 foot pounds of disturbance energy per pound of affected water. Since this energy is applied and distributed to the water beginning at the ship's bow and continuing to a few lengths astern, the energy is being applied and dissipated in this case over a flow length of at least 1500 ft.

If a similar energy analysis were applied to the white water wakes of the destroyers as depicted in Ref. [4], the smaller wake dimensions, shorter flow length, and greater horsepower output would undoubtedly yield much higher unit values of the disturbance energy.

In light of the low or diluted energy level of 0.14 foot pounds per pound and the elapsed time in excess of 12 min encountered in the first test of the John Hulst it appears quite reasonable that bubbles were lacking. In contrast the powerhouse canal studies of Section IV, while involving a much lower basic velocity, possessed nearly twice the unit disturbance energy, a much shorter but adequate generating length and a much fresher water sample. As a result measurable gas was present in that case.

Another basic difference in these two contrasting tests is the temperature of the water. Quite apart from the effect of temperature on gas solubilities is the effect on the viscosity of the liquid. The viscosity for the 51 F water temperature of the Superior test is nearly 40 per cent higher than that of the 74 F water of the canal test. Since the generation of free gas is primarily traced to the generation and maintenance of vorticity [1] in the liquid, it is apparent that reduction of the vorticity by increased viscous action should materially depress the generation and maintenance of the free gas. Measured evaluations of these viscous influences are not known.

Another rather surprising aspect of the Lake Superior tests was the persistent evidence of acoustic attenuation with values increasing from their incidence at about 160 kc to the limits of the apparatus at 200 kc. These frequencies of attenuation indicate the presence of bubbles of about 0.0017-in. diameter and smaller. This attenuation was observed in all of the tests including the one with the ambient lake water undisturbed by the target ship. The existence of stabilized bubbles of this size has been noted by Turner [9] in tests with water containing considerable particulate matter. However, with cleaner water these larger sizes disappeared and stability was achieved with smaller sizes more in accord with Strasberg. Strasberg [2] in his tests found that stabilized bubbles were less than about 0.0002 in. in diameter.

It must be noted too that the type of attenuation observed in the 160 to 200 kc range of these tests may be due to real bubbles which are resonant at these frequencies but may also be due to the broad band attenuation

effects of large concentrations of even smaller bubbles [6]. Since the acoustic equipment did not provide readout above 200 kc there is some question as to the true meaning of the attenuations shown in the 160 to 200 kc range.

An alternate explanation for these smaller bubbles may also be rationalized from the pressure history of the test water and earlier measurements of dissolved oxygen values in the lake. These measurements [8], made in August 1957, are as follows:

Depth	Dissolved oxygen (ppm)	Temp. °F
Surface	9.6	63
50	9.7	60.5
80	11.4	44.0
200	12.2	40.0

Since the above oxygen values are in general accord with standards [Ref. 10, Table 231] of oxygen solubility for the given temperatures, it appears that subsurface diffusion of gases in response to thermal and pressure gradients tends to increase the concentrations of dissolved gases at the lower levels of the lake. If this is true then any welling up of lower level lake waters would tend to produce conditions of gas supersaturation and consequent dissolution of free gas in the surface waters. Gas stability conditions were also probably complicated by the general seasonal cooling off occurring at the time of test.

The possibility of upwelling occurring in the test waters is verified by the studies of others in this same area of the lake. Bathythermograph data [11] in 1956 indicated that isotherms, which are normally fairly flat in the central region of the lake, are radically changed under the influence of strong NNW winds. This change results from the wind shear induced movement of warm surface waters toward the windward Wisconsin shore some twenty-two miles away and the consequent movement of much colder water to the surface on the leeward Minnesota side of the lake. Figure 4 shows the nature of such changes in the test area. Since winds of similar character prevailed during the gasification measurements, there is reason to believe that these

measurements may have detected gases in a transient process of dissolution rather than stabilized gas bubbles. Blanchard and Woodcock [12] discuss certain aspects of the gas saturation-evolution problem but indicate that the present state of knowledge does not support firm predictions.

VI. MEASUREMENT OF MISSISSIPPI RIVER WATER DISTURBED BY A TOW BOAT

This test was conducted for the purpose of determining the nature of the gasification and decay of gasification which would occur with major disturbance of Mississippi River water.

The tests were conducted because the earlier tests on Lake Superior, which are described in Section V, failed to clearly establish the propeller-generated gasification of Lake Superior water. While additional tests might have been conducted on Lake Superior, problems existed with the scheduling of work boats, target boats, and personnel. This suggested the possibility of conducting tests on Lake Pepin which is a wide reach of the Mississippi River some 60 miles downstream of the Laboratory.

The tests were conducted on October 25, 1962 in the navigation channel through the Lake at about mile 784.5 on the river navigation marking system. This point is about 1-1/2 miles downstream of the head of the Lake and about 1/4 mile off the south shore where the river is about two miles wide and 20 ft deep.

The weather conditions during the tests were sunny with occasional clouds. The winds were from the NW at about 15 mph and produced waves of about 2 ft earlier in the day diminishing slightly during the day. Whitecaps existed all day. The air temperature was 30 F and the water temperature 48 F.

The water had a brownish cast from suspended organic fines. Van Slyke total gas measurements indicated that the water was about 3 per cent undersaturated for the prevailing temperature.

The target ship was the Baby Lere operated by the Midwest Towing Company of Chicago. This tow boat was pushing eleven barges of coal having a pay load slightly in excess of 15,000 tons. The boat was moving upstream with a relative water speed slightly in excess of 7 mph. The barges were arranged in a line of four with three abreast to give a total tow length of about 900 ft, a width of about 100 ft, and a draft of about 8.5 ft.

Each of the tow's twin screws was driven with 1200 hp at a speed of about 280 rpm. The screws were in a modified tunnel or nozzle mounting and were of 8-ft diameter. The screw pitch was 84 in. and the construction was of stainless steel. The skipper considered the screws to be rough in action because of a long season's operation in water containing debris. Because of this, top speed was not being used at the time of test.

The transducers for these tests were the same as those in the Lake Superior tests but were used in an open mounting without the plexiglas housing chamber and were positioned at a depth of about 3 ft. The transducers were raised free of the water and air drained prior to each recording.

The rather brown and unclear water of the lake became very gray and dirty looking in the wake directly astern of the boat. This was due to the powerful action of the propeller in disturbing the blue gray clay of the lake bottom. Microscopic examination of these solids, as they were found in the Van Slyke samples, established them as flocculations composed of mineral particles ranging from 0.002 to 0.010-mm diameter. The turbulent wake of the tow was such as to maintain these mineral solids in suspensions for a prolonged period. They were still visually evident when operations were suspended in the wake 1-1/4 hr after passage of the tow.

It had been intended to move into the wake as rapidly as possible following the passage of the tow in order that a fresher wake be obtained than was the case in the Lake Superior tests. In this case the test equipment was anchored in the wake in slightly over 5 min but difficulties with the recorder resulted in first records being obtained at a wake age of about 15 min. A total of four records was made in the wake up to an age of 40 min. These records were followed by an ambient lake water test several hundred feet away from the wake area. No free gas bubbles were visually evident in the wake water even at the first observation when the wake was of age 5 min.

Analysis of the graphic plottings of the test recordings for attenuation versus frequency in the 20 to 200 kc range failed to yield any evidence of the presence of free air bubbles. The readout plottings for the open transducer setting employed for these tests were different from those which previously employed the housing chamber. In this case divergence signal effects were noted when altering the transmission distance by traversing the pick-up. When using the housing it had been noted that saturation levels

were obtained, thus producing little evidence of influence from changing transmission distance (3/4 in. to 4 in.).

The heavy concentration of mineral solids in the wake water was considered to have had negligible influence on the gas attenuation measurements which were being employed in these tests. Earlier studies [13] have indicated that such solids have a scattering or blocking influence for megacycle frequencies but not for the frequency range of these tests.

It must be concluded from these measurements that, despite the very extensive boundary system and powerful turbulence of the target, free gas was not present in the wake of age 15 min or greater for measurements in the frequency range 20 to 200 kc. It may be speculated that the absence of free gas is due primarily to the low and seasonally declining temperature of the water. This temperature condition could contribute to increased viscous damping of vorticity and increased solubility of gases tending to undersaturation.

VII. CONCLUSIONS

1. The turbulent vorticity created by a shearing motion in water is capable of freeing gases dissolved in the water. Acoustic observations have established that vaporous cavitation is not a necessary part of the gas release mechanism.

2. The size and concentration of the released gas bubbles appear to be some function of the intensity and duration of the dynamic disturbance applied to the water and of the pressure, temperature, and relative gas saturation of the water.

3. The low level shear energy conditions inherent to a ship's boundary layer will produce gasification at low relative speeds if the duration of exposure is sufficient. In these tests velocity as low as 4 fps produced measurable gasification when the shear exposure endured over several hundred feet of simulated hull flow. The larger sizes of bubbles produced (≈0.0025-in. diameter) are considered suitable nuclei for cavitation on a downstream propeller because they have a critical expansion pressure which is

only slightly less than vapor pressure. The bubble size will increase with increasing velocity.

4. The high level shear energy conditions inherent to a propeller action will produce substantial gasification with very brief flow exposure. If the high shear is accompanied by low ambient pressures heavy gas production will occur, but some gasification has even been observed [4] in submarine wakes with submergence in excess of 100 ft. The dynamic pressure mechanisms inherent to such gasification are not fully understood.

5. The relative gas saturation of a water is critical to the release of gas under dynamic conditions. In undersaturated waters release of gas may be difficult to achieve and resolution of any released gases may be very rapid. In oversaturated waters gas release is easily triggered and can seriously hamper acoustic studies if release occurs on the active surface of transducers.

6. The generation and maintenance of free gas in water appears to be sensitive to temperature-viscosity influences on vorticity. Cavitation and acoustic studies should, therefore, involve a full range of prototype temperature conditions until the nature of this influence is more fully understood.

7. Under equilibrium conditions the total gas content of Lake Superior water increased with depth. Meteorological conditions which produce upwelling or vertical rise of deep waters may contribute to oversaturation and may result in abnormal cavitation and acoustic problems. Additional information is needed on the total gas and relative saturation values which exist at sea under ambient conditions normal to naval operations.

8. The use of acoustic frequencies in the range from 20 to 200 kc is believed suited to gas measurements in water tunnels or active shear zones on ship components. Increasingly higher frequencies will be required to detect

the presence of the bubbles as their size decay progresses with time. The measurable decay time may vary from a few seconds to many hours depending on the surrounding conditions and frequencies employed.

9. Secondary evidence [12], [14], [15] indicates that various factors such as the exchange of particulate matter at the free surface, gas solubility, bubble coalescence properties of the water, etc., may be markedly different with sea waters and fresh waters. Gas measurements in fresh water should, therefore, be conservatively applied to sea water conditions until further data are acquired.

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F I G U R E S

(1 through 4)

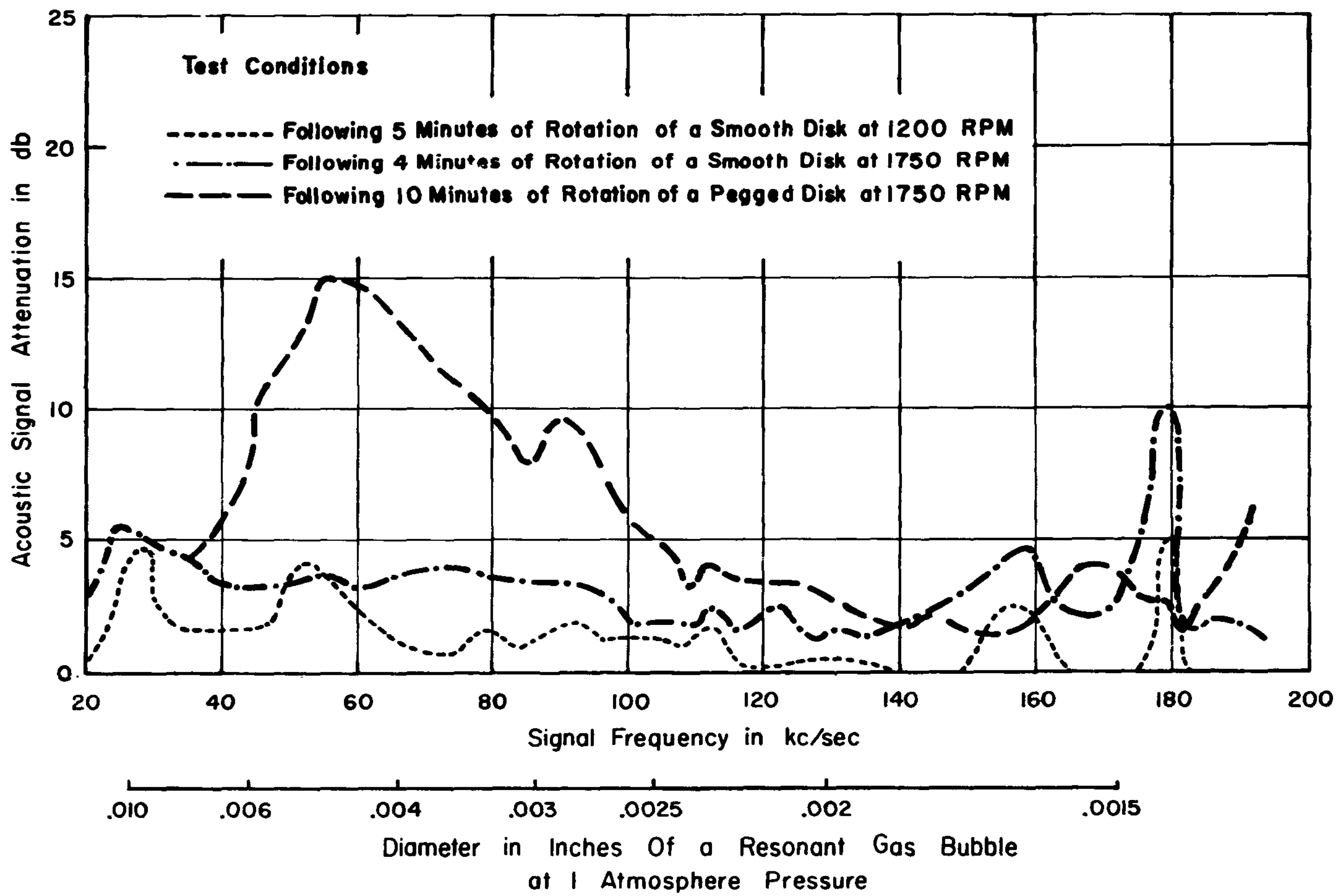
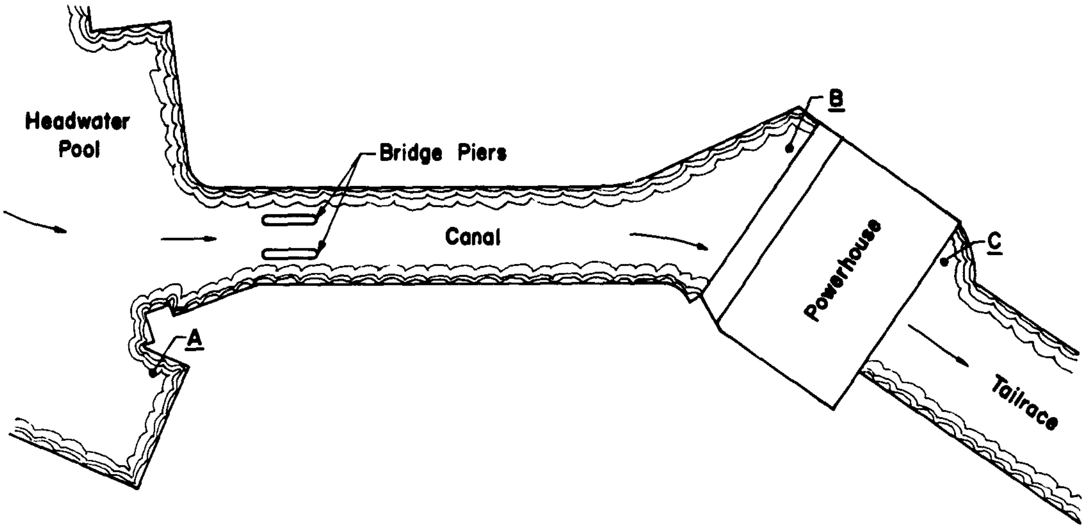
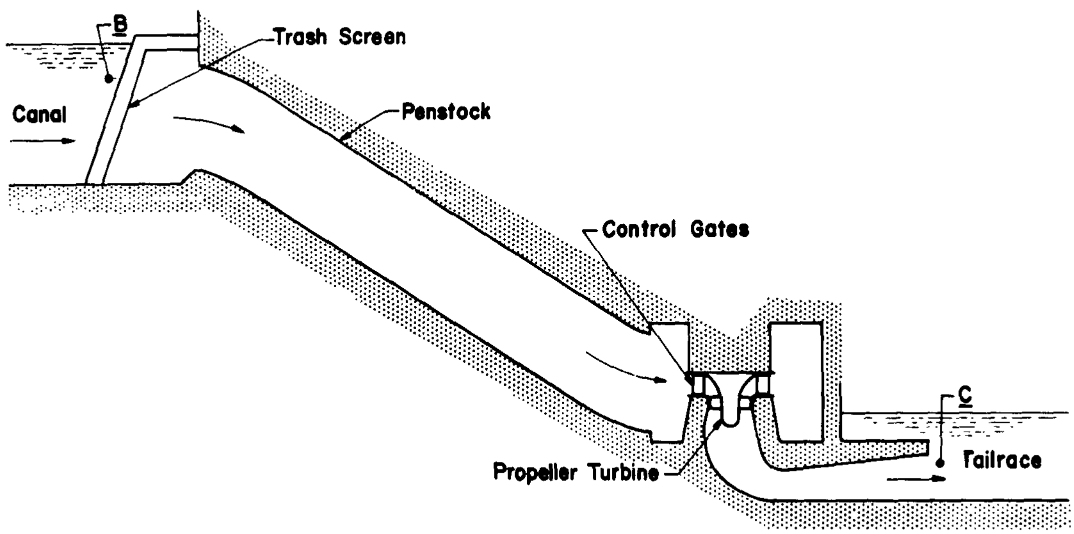


Fig. 1 - Spectrum of Acoustic Transmission through the Water of a Small T[illegible]
which has been Mechanically Disturbed in Various Ways



Plan View of Powerhouse at St. Anthony Falls



Section of Powerhouse at St. Anthony Falls

Fig. 2 - Orientation of Test Points for Gasification Tests with a Hydroelectric Propeller Turbine

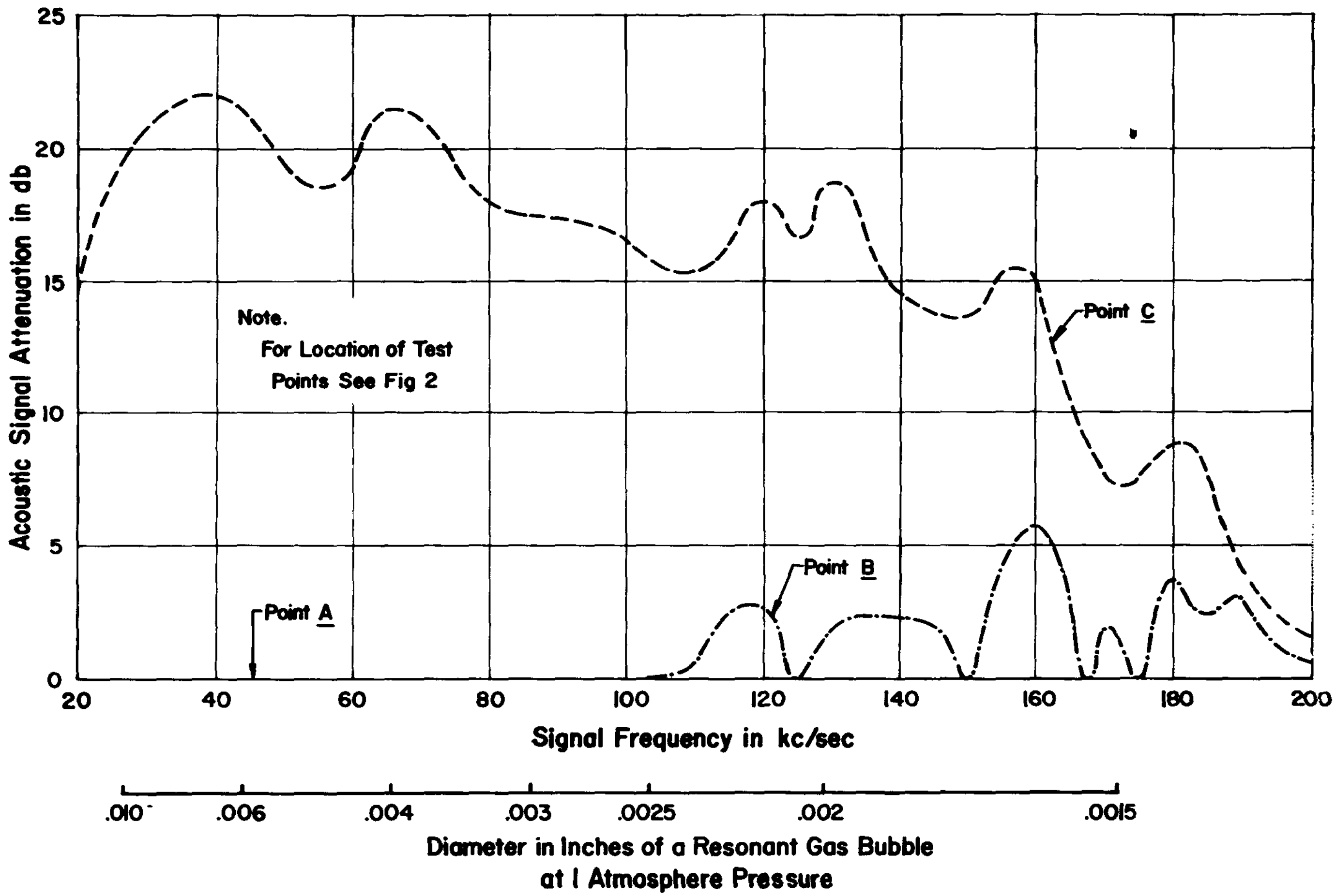
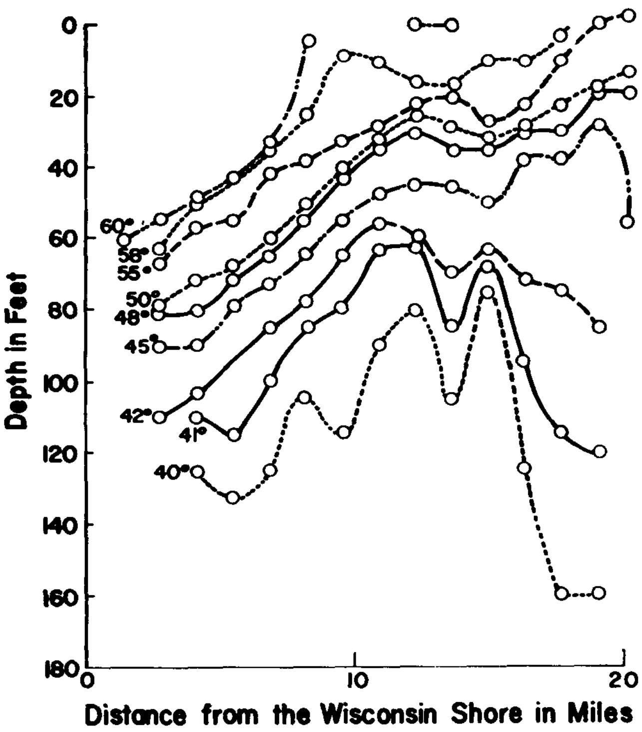
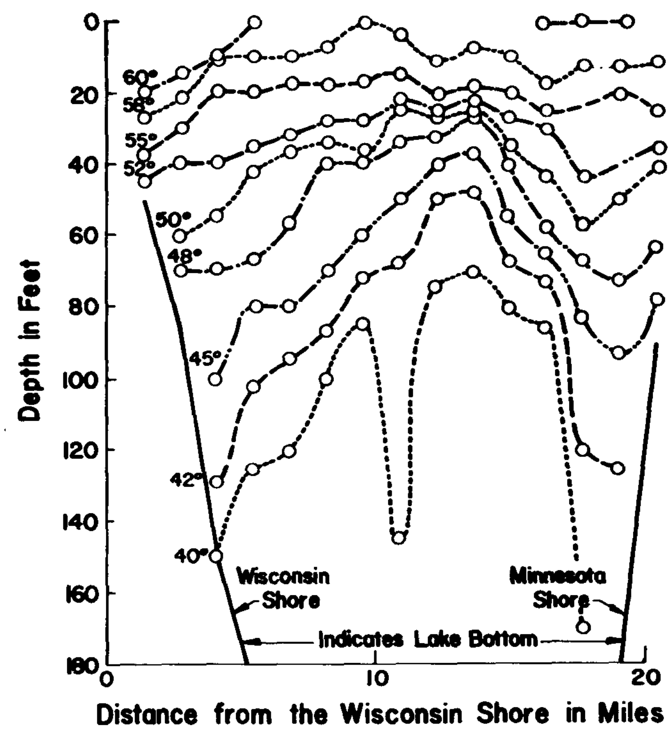


Fig. 3 - Spectrum of Acoustic Transmission through Test Waters of a Hydroelectric Power Plant



Isotherm Distribution for a high
Wind from the Minnesota Shore August, 1956



Isotherm Distribution for Zero
Wind Conditions July, 1956

Fig. 4 - Typical Isotherm Distributions for the Lake Superior Test Area
(from Ref. [11])

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